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TWO-WAY AND THREE-WAY DOPPLER TRACKING VIA TDRSS

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ABSTRACT

This technical memorandum documents part of the work performed under Task Assignment 584, Tracker Calibration. This task requires performance of analyses to evaluate errors incurred in a number of tracking configurations associated with the Tracking and Data Relay Satellite System (TDRSS). The document describes the modeling used to simulate three-way Doppler data from TDRSS and lists the errors computed for short spans of three-way and two-way data in a launch configuration. An analysis of short spans of simulated bilateration data for the Applications Technology Satellite-6 (ATS-6) is also included. An evaluation of the use of two-way Doppler data via TDRSS to track the Interim Upper Stage (IUS) of interplanetary missions is described briefly; this study is documented more fully in Technical Memorandum CSC/TM-76/6268.

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SECTION 1 - INTRODUCTION

The Tracking and Data Relay Satellite System (TDRSS) will provide a number of new tracking modes. One of these is the hybrid or three-way mode, in which the forward link from the ground is relayed to the user spacecraft by one of the TDRS satellites but the return signal from the user is received and transmitted to the ground by both the forward-link TDRS and one of the other TDRS's (see Figure 2-1). The result is a type of data with a very high information content, so that relatively short tracking periods can provide useful trajectories. This report documents a preliminary error analysis of three-way Doppler data as applied to the tracking of a trajectory following burnout and compares the results with those of a similar analysis in which conventional two-way data were alternated between the two TDRS relays.

Another possible application of TDRSS is to track the Interim Upper Stage (IUS) of an interplanetary mission immediately following injection. This report contains a description of the program modifications which were made in order to perform error analyses for this configuration. The analyses themselves are documented in Reference 1.

Also included in this report are the results of an analysis to determine the feasibility of using two short spans of bilateration data from the geosynchronous relay satellite to obtain a reliable relay ephemeris between these data spans. Such a procedure may be useful if TDRSS coverage of a user spacecraft is required shortly after a maneuver of the TDRS involved. An Applications Technology Satellite-6 (ATS-6) tracking configuration was used in this analysis.

SECTION 2 - THREE-WAY DOPPLER ANALYSIS

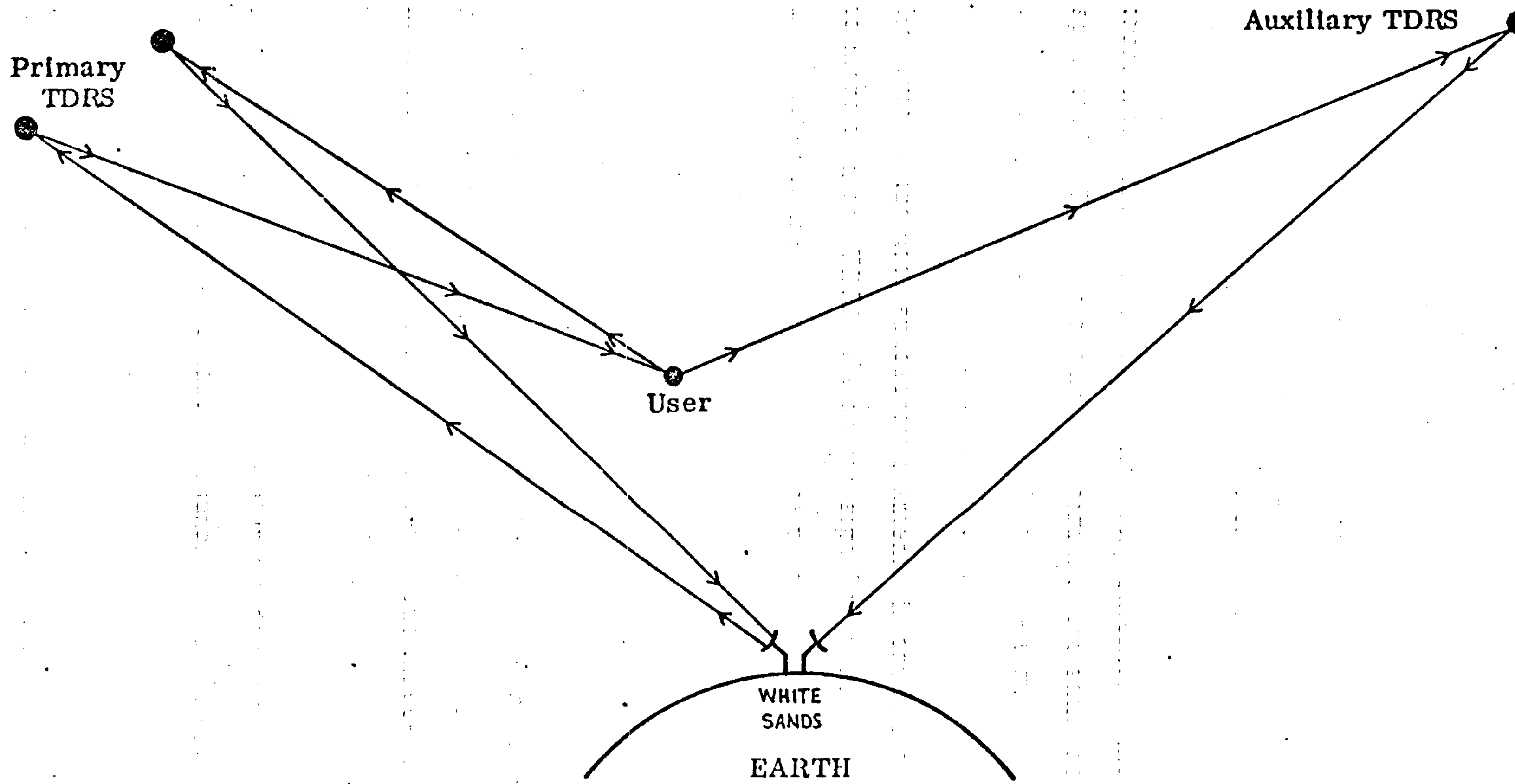
2.1 DESCRIPTION OF THE MEASUREMENT

The three-way range and Doppler measurements occur in a type of data that will become available from the Tracking and Data Relay Satellite System (TDRSS). They are taken in conjunction with the more conventional two-way range and Doppler measurements; the geometry associated with these measurements is shown in Figure 2-1. In normal satellite-to-satellite tracking (SST), the tracking signal is transmitted from the ground to the relay satellite, which retransmits it to the user spacecraft. The user returns the signal to the same relay satellite, which in turn passes it to the tracking station. This is the signal path shown in the left-hand portion of Figure 2-1 and is used to generate the two-way measurements.

However, if the user spacecraft's antenna is capable of transmitting simultaneously to more than one TDRS, the return signal transmitted by the user may be received and relayed to the ground by both the primary TDRS (i.e., the one which relayed the forward link) and one of the other relay satellites (referred to here as the auxiliary TDRS). The return link via the auxiliary TDRS is shown in the right-hand portion of Figure 2-1 and is used to generate the three-way measurements.

Since the return signals from both TDRS's are received simultaneously on the ground using different but adjacent antennas, the resultant data file will contain pairs of two-way and three-way measurements with the same time tag. The information provided by such a file of two-way and three-way measurements is approximately the same as would be provided by simultaneous two-way tracking from both TDRS's. Since this provides two quite distinct geometries simultaneously, it is expected to be extremely useful in situations where only a limited tracking time is available, particularly in launches and maneuvers.

The method has disadvantages since it requires that the user spacecraft have sufficient transmitting beam width to reach both TDRS's simultaneously and that it be in sight of both TDRS's. Although both range and Doppler data will be available in



NOTE: The forward link if transmitted via the primary TDRS. In conventional two-way measurements, the signal returns to the station via the primary TDRS; in the three-way measurement, the signal returns to the station via the auxiliary TDRS.

The diagram is not drawn to scale.

Figure 2-1. Geometry of Three-Way and Two-Way Doppler Tracking the three-way mode, for many configurations the range data are not expected to provide any additional accuracy. For this reason, the analysis described in this section was performed using only Doppler data; analyses using both range and Doppler data will be included in a subsequent report.

2.2 SOFTWARE USED

In order to perform error analysis of three-way data, a method was used which is similar to that used earlier for Doppler difference data (see Reference 2). This method does not provide a realistic simulation of the signal transmission and reception times, but does compute partial derivatives with sufficient accuracy for the purposes of error analysis.

From Figure 2-1 it can be deduced that to a good approximation, the three-way round-trip range is the sum of the one-way ranges via the two TDRS's, i.e.,

$$R_{3\text{-way}} = \frac{R_1}{2} + \frac{R_2}{2}$$

where R_1 and R_2 are the round-trip ranges via the two TDRS's. The same relationship will apply to the range rates, and hence to the Doppler measurements, i.e.,

$$D_{3\text{-way}} = \frac{1}{2} (D_1 + D_2)$$

The three-way Doppler measurement is then computed as the mean of the two corresponding two-way Doppler measurements. The partial derivatives will behave the same way:

$$\frac{\partial D_{3\text{-way}}}{\partial x} = \frac{1}{2}\left(\frac{\partial D_1}{\partial x} + \frac{\partial D_2}{\partial x}\right)$$

The analysis was performed by using the Navigation Analysis Program (NAP) to simulate two-way measurements from each of the two relay satellites involved. The measurements and partial derivatives computed in each case were saved on intermediate files and passed to a standalone program which used the two measurements with corresponding time tags to compute the three-way measurement and partial derivatives. An output file was generated which contained both three-way and two-way measurements for as long as the user spacecraft was in sight of both relay satellites; when the user moved out of sight of the auxiliary relay, only the two-way data from the primary relay were included. This file was then passed back to NAP which used it to accumulate the normal matrix; this matrix was in turn passed to the associated covariance analyzer (NAPCOV) which performed the error analysis.

2.3 ANALYSIS PERFORMED

In order to obtain preliminary estimates of the usefulness of the three-way data, error analyses were attempted for two launch configurations:

1. A shuttle launch from the Eastern Test Range (ETR) using TDRS East as the primary relay and the spare TDRS as the auxiliary
2. A shuttle launch from the Western Test Range (WTR) using TDRS West as the primary relay and TDRS East as the auxiliary

When these analyses were attempted, it was found that the visibility of the WTR launch from TDRS East (the auxiliary relay) was marginal, with the ray paths between TDRS East and the shuttle passing within 400 kilometers of the Earth's surface for almost every data point. Since 400 kilometers was the height chosen for occultation by the atmosphere, almost all the three-way data were excluded from the solution. Becuase of this, it was concluded that three-way tracking of such a launch will require use of the spare TDRS as the auxiliary relay. Due to time limitations, analysis of the WTR launch using the spare TDRS was not completed. Therefore, only the results obtained for the ETR launch will be reported here.

The user orbit utilized for the ETR launch had an inclination of 28.7 degrees and an altitude increasing from 167 kilometers at epoch to 243 kilometers

30 minutes later. Data spans were analyzed beginning at epoch, with durations of 4, 6, 10, 15, 22, and 30 minutes. Because the auxiliary relay (i.e., the spare TDRS) lost sight of the user spacecraft at approximately 6 minutes from epoch, all data taken after this time consisted only of two-way measurements via TDRS East, which in turn lost sight of the user after approximately 27 minutes. The solve-for parameters were the components of the user state vector at epoch; the data characteristics and the consider parameters used are listed in Table 2-1. For each tracking schedule, the computed errors at epoch were transformed into radial, along-track, and cross-track (HLC) coordinates and propagated through 100 minutes (approximately the period of the user orbit). The maximum values attained by the computed errors during this time are tabulated in Table 2-2.

2.4 TWO-WAY ANALYSIS

For the purpose of comparison with the results of the three-way analysis, error analyses were made in which the same user trajectory was tracked using two-way data, with the relay satellite used alternating between TDRS Spare and TDRS East. Such a data distribution would approximate three-way coverage for a user whose antenna was not capable of transmitting simultaneously to two relay satellites. The noise value, data rate, and error model used were the same as those applied to the three-way analysis. The data were arranged in 2-minute segments, and the segments were alternated between the two relays for as long as both relays were visible. Thereafter, continuous data from TDRS East was used. Because TDRS Spare was the first relay to lose sight of the user, the first 2-minute span was always taken via TDRS Spare. The same error propagation procedure was used as in the three-way analysis. Due to time limitations, only a subset of the three-way runs was repeated with two-way tracking; these corresponded to data spans of 4, 6, 15, and 30 minutes. The results are listed in Table 2-3.

Table 2-1. Data and Error Models Used in the Three-Way Analysis (1 of 2)

USER SPACECRAFT ELEMENTS

Component	ETR Launch	WTR Launch
North latitude (deg)	24.77679	17.234622
East latitude (deg)	300.496986	233.68555
Radius (km)	6541.867	6561.442
Horizontal flight path angle (deg) (inertial)	-0.0714	-0.0015
Azimuth (deg) (inertial)	105.2719	192.6711
Speed (km/sec) (inertial)	7.839636	8.14739

TDRS LOCATIONS

TDRS West	188° east longitude, 5° inclination
TDRS Spare	243° east longitude, 5° inclination
TDRS East	318° east longitude, 5° inclination

DATA

S-band Doppler only:	Two-way and three-way simultaneously, while both relays in sight. Two-way only, otherwise.
Noise value:	0.002 Hz round trip for both data types
Data rate:	Six points/minute for each data type

ERROR MODEL

TDRS state vectors (maximum uncertainty in data span):[1]

H (meters):	20
L (meters):	70
C (meters):	140
$\dot{H}$ (mm/sec):	3.7
$\dot{L}$ (mm/sec):	1.5
$\dot{C}$ (mm/sec):	10.0
Solar reflectivity:	0.14 (for area/mass = 0.02 m^2/kg)

[1] The relay satellite state vector uncertainties assumed were the same as those in Table 3-3 of Reference 1, and the comments in Section 3.2 of that document apply also to the runs described here.

Table 2-1. Data and Error Models Used in the Three-Way Analysis (2 of 2)

ERROR MODEL (Cont'd)

Station Geodetics:	10 meters each direction
Drag:	10 percent (for $C_D A/M = 10^{-3}$ m^2/kg)
Geopotentials:	
GM:	0.0001 percent
C(2, 0):	0.0007 percent
C(3, 0):	0.44 percent
C(4, 0):	1.8 percent

Table 2-2. Computed Errors in Trajectory of Vehicle Tracked by Two-Way and Three-Way Doppler Data

Tracking Time (minutes)	Number of Points (Two-Way)	Number of Points (Three-Way)	Maximum RSS (meters)	Maximum Noise (meters)		Maximum Consider (meters)	Major Consider Parameters
4	24	24	354	H	59	34	Drag, relays, GM
				L	307	174	Drag, relays, GM
				C	27	18	Relays, drag
6	36	34	196	H	23	30	Drag, relays, GM
				L	120	155	Drag, relays, GM
				C	10	18	Relays, drag
10	60	34	88	H	8	14	Drag, relays, GM
				L	40	76	Drag, relays
				C	3	17	Relays, drag
15	90	34	60	H	3	10	Drag, GM, relays
				L	14	56	Drag, GM, relays
				C	1	16	Relays, drag
22	132	34	62	H	1	11	Drag, GM, relays
				L	5	59	GM, relays, drag
				C	0.5	16	Relays, drag
27	161	34	79	H	0.8	15	GM, relays, drag
				L	5	76	Relays, GM, drag
				C	0.5	17	Relays, drag

NOTES: Data Rate = 6/minute for each type; Propagation = 1 hour, 40 minutes from epoch (data begin at epoch)

Table 2-3. Computed Errors in Trajectory of Vehicle Tracked by Spans of Two-Way Data Alternating Between Two TDRS's

Data Length (minutes)	Number of Points (TDRS East)	Number of Points (TDRS Spare)	Maximum RSS (meters)	Maximum Noise (meters)		Maximum Consider (meters)	Major Consider Parameters
4	12	12	720	H	136	31	Drag, relays, GM
				L	700	159	Drag, relays, GM
				C	61	18	Relays, drag
6	12	22	230	H	24	38	Drag, relays, GM
				L	122	194	Drag, relays, GM
				C	20	18	Relays, GM
15	66	22	58	H	4	9	Drag, GM, relays
				L	19	52	Drag, GM, relays
				C	1	16	Relays, drag
27	137	22	92	H	0.7	18	Relays, GM, drag
				L	3.4	90	Relays, GM
				C	0.3	17	Relays, drag

NOTES: Data type = alternating 2-minute spans of two-way Doppler data from TDRS East and TDRS Spare, beginning with TDRS Spare

Data rate = 6/minute

Propagation = 1 hour, 40 minutes from epoch (data begin at epoch)

2.5 CONCLUSIONS

The computed errors listed in Table 2-2 indicate that very short spans of three-way data are capable of providing useable state vectors. The optimum tracking time in this configuration is around 15 minutes. The precision of the solution arises from the geometrical advantage of using two relay satellites, which provide a stereoscopic view of the user trajectory. This advantage is also present in the two-way tracking analysis shown in Table 2-3, so that the errors computed for the longer two-way data spans are comparable to those computed for the three-way data. However, for very short tracking times where the errors are dominated by the effects of data noise, the three-way data provide twice the number of measurements, and hence considerably smaller computed errors than do the two-way data. The two-way data also have an optimum tracking time of 15 minutes in this configuration.

SECTION 3 - IUS ANALYSES

3.1 INTRODUCTION

In response to a Jet Propulsion Laboratory (JPL) request for an analysis of the capability of TDRSS to provide tracking support for the Interim Upper Stage (IUS) of interplanetary launches, a series of error analyses was performed. Each of the four IUS trajectories supplied by JPL was tracked for up to 1 hour from each of the three TDRSS relays, using only one relay in each tracking configuration. The results of the study are documented in Reference 2.

3.2 PROGRAM MODIFICATIONS

In order to restrict the data included in the analysis to points within the maximum pointing angles of the TDRS antennas, NAP was modified to compute the pointing angles at each data point and to eliminate those points whose pointing angles were outside the limits for TDRS. The following describes the algorithm used to compute the antenna pointing angles.

It is assumed that the reference orientation of the TDRS antenna is pointing towards the center of the Earth and that it can be rotated by up to 22-1/2 degrees from this orientation in the east-west direction and by up to 31 degrees in the north-south direction. For given relay and target position vectors $\vec{r}_R$ and $\vec{r}_T$, it is therefore necessary to compute the east-west and north-south pointing angles subtended by the target spacecraft at the relay satellite.

A new Earth-centered Cartesian coordinate system is defined such that:

1. The relay satellite lies on the negative y-axis
2. The x-axis lies in the Earth's equatorial plane, perpendicular to the y-axis
3. The z-axis extends northwards, perpendicular to the other two axes

For a right-handed coordinate system, the positive x-axis will extend eastwards when viewed from the relay satellite. This system may be obtained from the inertial coordinate system by:

1. First rotating about the z-axis until the relay satellite lies in the y-z plane with negative y, and then

2. Rotating about the new x-axis until the relay satellite lies on the negative y-axis

If in the inertial system the relay satellite position vector is $\vec{r}_R = (x_R, y_R, z_R)$ and the target position vector is $\vec{r}_T = (x_T, y_T, z_T)$, and if $\rho \equiv \sqrt{x_R^2 + y_R^2}$ and $r \equiv \left| \vec{r}_R \right|$, then the rotation matrix for the first rotation is

$$M_1 = \begin{bmatrix} -\frac{y_R}{\rho} & \frac{x_R}{\rho} & 0 \\ -\frac{x_R}{\rho} & -\frac{y_R}{\rho} & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad (3\text{-}1)$$

and the matrix for the second rotation is

$$M_2 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \frac{\rho}{r} & -\frac{z_R}{r} \\ 0 & \frac{z_R}{r} & \frac{\rho}{r} \end{bmatrix} \qquad (3\text{-}2)$$

The net rotation matrix is then the following:

$$M = M_2 M_1 = \begin{bmatrix} -\frac{y_R}{\rho} & \frac{x_R}{\rho} & 0 \\ -\frac{x_R}{r} & -\frac{y_R}{r} & -\frac{z_R}{r} \\ -\frac{x_R z_R}{r\rho} & -\frac{y_R z_R}{r\rho} & \frac{\rho}{r} \end{bmatrix} \qquad (3\text{-}3)$$

In the rotated coordinate system, the relay position vector is

$$M\vec{r}_R = \begin{bmatrix} 0 \\ -r \\ 0 \end{bmatrix} \qquad (3\text{-}4)$$

and the target state vector is

$$M\vec{r}_T = \begin{bmatrix} x_A \\ y_A \\ z_A \end{bmatrix} \qquad (3\text{-}5)$$

where

$$x_A = (x_R y_T - y_R x_T)/\rho$$

$$y_A = -(\vec{r}_R \cdot \vec{r}_T)/r$$

$$z_A = [r^2 z_T - (\vec{r}_R \cdot \vec{r}_T) z_R]/(r\rho)$$

If the antenna pointing angles subtended by the target at the relay satellite are denoted by E for the east-west pointing angle and by N for the north-south pointing angle, then

$$\tan E = \frac{x_A}{y_A + r} \qquad (-180^o < E < 180^o) \qquad (3\text{-}6a)$$

and

$$\sin N = \frac{z_A}{|\vec{r}_T - \vec{r}_R|} \qquad (-90^o < N < 90^o) \qquad (3\text{-}6b)$$

In the computer program, the angle E can be placed in the correct quadrant by use of the DATAN2 function as follows:

E = DATAN2 (XA, YA + R)

Alternatively, the coordinate rotation in Equation (3-3) may be used to compute the Earth-centered angles subtended by the target relative to the relay position. These may be computed as

$$\tan E' = \frac{x_A}{(-y_A)} \qquad (3\text{-}7a)$$

and

$$\sin N' = \frac{z_A}{r} \qquad (3\text{-}7b)$$

where the angle E' is again evaluated using the DATAN2 function, i.e.,

E' = DATAN2 (XA,-YA)

3.3 ANALYSIS AND CONCLUSIONS

Tracking schedules of up to 60 minutes were analyzed for each of the four JPL trajectories, using two-way Doppler data for each of the three TDRSS relay satellites. The details of these analyses are given in Reference 2. It was found that when only one relay satellite is used, the errors are, in general, dominated by the effects of data noise. However, if at least 20 minutes of data are taken using an appropriate relay satellite (usually TDRS East), sufficiently accurate state vectors can be obtained. Tracking configurations which make use of more than one relay satellite will be examined in a future report.

SECTION 4 - ATS-6 BILATERATION

4.1 CONFIGURATIONS ANALYZED

The objective of this study was to determine the accuracy with which the relay satellite state vector can be determined using only two short data spans, 1 hour apart. Should such a data configuration prove effective, it could be used to provide the relay ephemeris for an SST tracking sequence or for other experiments taking place in the intervening hour. For these runs, an ATS-6 tracking exercise was simulated, with ATS-6 stationed at 220 degrees east longitude. The primary tracking station was Rosman, and runs were made using ground transponders at Santiago and Alaska, as well as an auxiliary tracking state at Mojave. The following three data combinations were analyzed:

1. Direct range and Doppler tracking from Rosman and direct range only from Mojave

2. Direct range and Doppler from Rosman and relay range and Doppler from Rosman to the Santiago ground transponder

3. Direct range and Doppler from Rosman and relay range and Doppler from Rosman to the Alaska ground transponder

Each combination provides a bilateration coverage of the satellite, but the first type has Doppler information on only one of the signal paths, since the Doppler equipment at Mojave can only provide sidetone data which is comparatively noisy. For each data combination, 5 minutes of tracking of each type were simulated at the beginning of the hour, and a second 5-minute pass of each type was simulated at the end of the hour. The data rate for all types was six per minute. The details of the data configurations and the error model are given in Table 4-1.

4.2 RESULTS AND CONCLUSIONS

The results of the analysis are given in Table 4-2. In each case, the table lists the maximum propagated errors within the data span (i.e., in the 80 minutes

Table 4-1. Information Used in the ATS-6 Bilateration Analysis (1 of 2)

ATS-6 ELEMENTS (True of Date)

X	-39811.350 km	$\dot{X}$	1.0109293 km/sec
Y	-13853.352 km	$\dot{Y}$	-2.9044619 km/sec
Z	-436.059 km	$\dot{Z}$	0.0215993 km/sec

EPOCH

August 31, 1975 at 00:00:00 UTC

GEODETICS

Location	North Latitude Deg	Min	Sec	East Longitude Deg	Min	Sec	Height (meters)
Rosman	35	11	56.60	277	7	28.19	823.4
Mojave	35	19	53.98	243	6	44.76	885.7
Santiago	-33	9	5.08	289	19	58.85	699.0
Alaska	64	58	19.20	212	29	13.38	339.1

TRACKING SCHEDULE (Times Referenced to Epoch)

0 minutes - 5 minutes: Direct tracking from Rosman (range & Doppler)
5 minutes - 10 minutes: Alternate data type
10 minutes - 70 minutes: No data
70 minutes - 75 minutes: Direct tracking from Rosman (range & Doppler)
75 minutes - 80 minutes: Alternate data type

DATA

Each run used direct tracking from Rosman (range and Doppler) and one other data type. Other data types used were:

(1) Direct tracking from Mojave (range only)
(2) Relay via ground transponder in Santiago (range and Doppler)
(3) Relay via ground transponder in Alaska (range and Doppler)

Noise values: Range (all types) = 1 meter (one way)
Doppler (all types) = 0.002 Hz (round trip)

Data Rate: Six points/minute for each type

Table 4-1. Information Used in the ATS-6 Bilateration Analysis (2 of 2)

ERROR MODEL

Consider Parameter	Value
ATS-6 solar reflectivity	10%*
Rosman station geodetics	10 meters each direction
Mojave station geodetics	10 meters each direction
Ground transponder geodetics	Not included
Direct-track range bias	10 meters one way
Ground-transponder range bias	25 meters one way
GM of Earth	0.0001%
C(2,0)	0.0007%
C(3,0)	0.44%
C(4,0)	1.8%

*Assuming ATS-6 mass = 1402 kg, ATS-6 area = 30 $\overline{m}^2$, ATS-6 reflectivity = 1.5

Table 4-2. Computed Errors in the ATS-6 Position From Short Spans of Bilateration Data

Data Type	Component	Maximum Errors in Data Span (meters)			Maximum Errors in 48-Hour Propagation (meters)		
		Noise	Consider	Major Consider Parameters	Noise	Consider	Major Consider Parameters
Direct track only: Range & Doppler - ROSR Range only - MOJR	H	640	18	GM, SP	1100	61	SP, Mojave bias, Mojave location
	L	660	330	Biases, station location	4400	350	GM, biases, station location, SP
	C	6100	320	Mojave bias, GM, Mojave location, SP	9100	320	Mojave bias, SP, GM, Mojave location,
Range and Doppler from ROSR (direct and via AGOB)	H	27	310	Biases, station location	32	370	Biases, station location
	L	230	2700	Biases, station location	270	3200	Biases, station location
	C	15	36	Biases, station location	15	55	Biases, station location
Range and Doppler from ROSR (direct and via Alaska)	H	6	20	Biases	7	55	SP, biases, GM
	L	19	270	Biases, station location	22	410	GM, biases, SP
	C	42	62	Biases, GM	45	84	Biases, GM

NOTES: Data in each run consisted of two 10-minute tracking intervals, separated by 1 hour, i.e., total time from beginning to end of data was 80 minutes. Each 10-minute interval contained 5 minutes of direct tracking from ROSR and 5 minutes of either direct track from MOJR (run 1) or relay data from ROSR via a remote ground transponder (runs 2 and 3). Data rate was 6/minute for all types.

Consider parameter abbreviations: Biases = range biases on the two data types (Mojave bias = bias on MOJR data only)
SP = Solar pressure
GM = Earth's gravitational constant

between the beginning of the first pass and the end of the last pass) and also the maximum error obtained in a 2-day propagation.

As expected, the Rosman and Mojave combination is less effective than the others, partly due to the absence of Doppler data from Mojave. The advantage of the Alaska data over the Santiago data may be explained by the geodetic coordinates listed in Table 4-1. Santiago and Rosman occupy almost the same longitude; this makes the measurement combination insensitive to along-track motion of the satellite, since such motion is approximately orthogonal to both signal paths. It nevertheless provides very good cross-track definition. In contrast, Alaska is sufficiently separated from Rosman in both latitude and longitude so that the data combination is sensitive to both along-track and cross-track motion. In a similar way, the fact that Mojave has almost the same latitude as Rosman may account for the large cross-track insensitivity of the Rosman-Mojave combination.

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